A Review of PV Inverter Technology Cost and Performance Projections

Presentation to

National Renewable Energy Laboratory

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Navigant Consulting, Inc. (NCI) evaluated the PV inverter technology and cost improvements required to meet U.S. DOE goals for 2020.

- The National Renewable Energy Laboratory (NREL) has a major responsibility in the implementation of the U.S. Department of Energy's (DOE) Solar Energy Technologies Program. Sandia National Laboratories (SNL) has a major role in supporting inverter development, characterization, standards, certifications, and verifications .
- The Solar Energy Technologies Program recently published a Multi-Year Technical Plan which establishes a goal of reducing the Levelized Energy Cost (LEC) for photovoltaic (PV) systems to \$0.05 - 0.10 / kWh by 2020.
- The Multi-Year Technical Plan estimates that in order to meet the PV system goal, PV inverter prices will need to decline to \$0.25-0.30 / Wp by 2020.
- DOE determined the need to conduct a rigorous review of the PV Program's technical and economic targets, including the target set for PV inverters.
- NREL requested that NCI conduct a review of historical and projected cost and performance improvements for PV inverters, including identification of critical barriers identified and the approaches government might use to address them.

Today, inverters are still described by many in the industry as the "Achilles' heel" of PV due to reliability issues.

COST:

- The "rule of thumb" in the industry is that, to be competitive with grid power, the installed cost of PV systems needs to drop down to around $3/W.
  - With current prices near $1/W, reducing the cost of inverters is crucial to reaching this target.

RELIABILITY:

- With expected lifetimes of 5 to 10 years and high "infant mortality" rates, the reliability of inverters is not satisfactory.

NREL's key questions regarding PV inverter cost and performance, and the role they should play, can be broken down into three key questions.

What are the critical cost and performance improvement needs for PV inverters that government should support to promote PV market growth?

- **Do PV inverters face challenges in meeting the U.S. DOE's Solar Energy Program Technologies targets?***
- **Is there a clear understanding and consensus for addressing key PV inverter challenges?**
- **What role should government play in addressing the key challenges that PV inverters face?**

* This includes the question: "Will inverters reach cost goal set by the Solar Energy Technologies Program?"

NCI's five step project approach provided the basis for addressing NREL's questions.

1. Historical Perspective
2. Future Performance and Cost Estimates
3. Challenges for Achieving Targets
4. Addressing Challenges for Achieving Targets
5. Government's Role in Addressing Challenges

What are the critical cost and performance improvement needs for PV inverters that government should support to promote PV market growth?

Steps 1–3: Do PV inverters face challenges in meeting the U.S. DOE's Solar Energy Program's targets?

Step 4: Is there a clear understanding and consensus for addressing key PV inverter challenges?

Step 5: What role should the U.S. DOE play in addressing the key challenges that PV inverters face?

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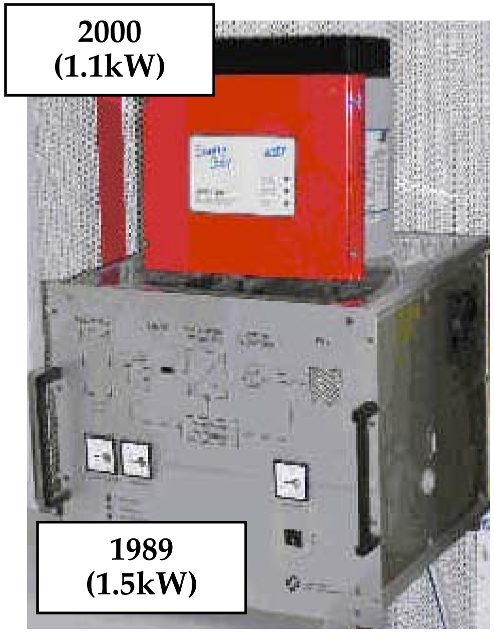
Despite modest production volumes, inverters have evolved significantly since the 1980s through continuous innovation.

1991	▪ The early 1990's saw the first large scale series production of PV inverters (SMA PV-WR).
1995	▪ First PV string inverter (SMA SB 700). Allows connection of modules in series, modular systems, higher system efficiency and reliability.
Late 1990s	▪ Basic data acquisition system, "plug-and-play" installation. ▪ Transformerless and High Frequency (HF) designs reach efficiencies above 95% ▪ Reliability improves. Warranties (2-5 years) offered.



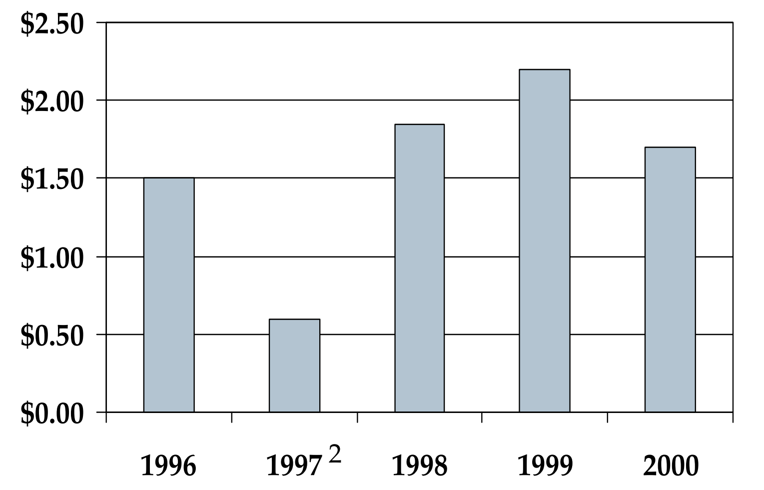
Recent Trends	▪ Sizes increase, leading to lower cost per kW. ▪ Data logging, communications, and diagnostics capabilities are added. ▪ Master-slave and other configurations allow higher efficiency at part load. ▪ Multi-String capability allows strings of PV modules operating under different conditions to be connected to a single inverter. ▪ Technology improvements allow transformerless designs to gain a competitive advantage.

Inverter prices reported by SEPA for the TEAM-UP initiative were in the $1.50/W to $2.00/W range for residential applications.[1]

- From 1996 to 2000, 644 residential installations were put in place, although inverter price data was not reported for all installations.

Year	Number of installations	kW	Average size (kW)
1996	91	350.93	3.86
1997[2]	83	309.08	3.72
1998	65	83.05	1.28
1999	201	296.3	1.47
2000	199	183.14	0.92

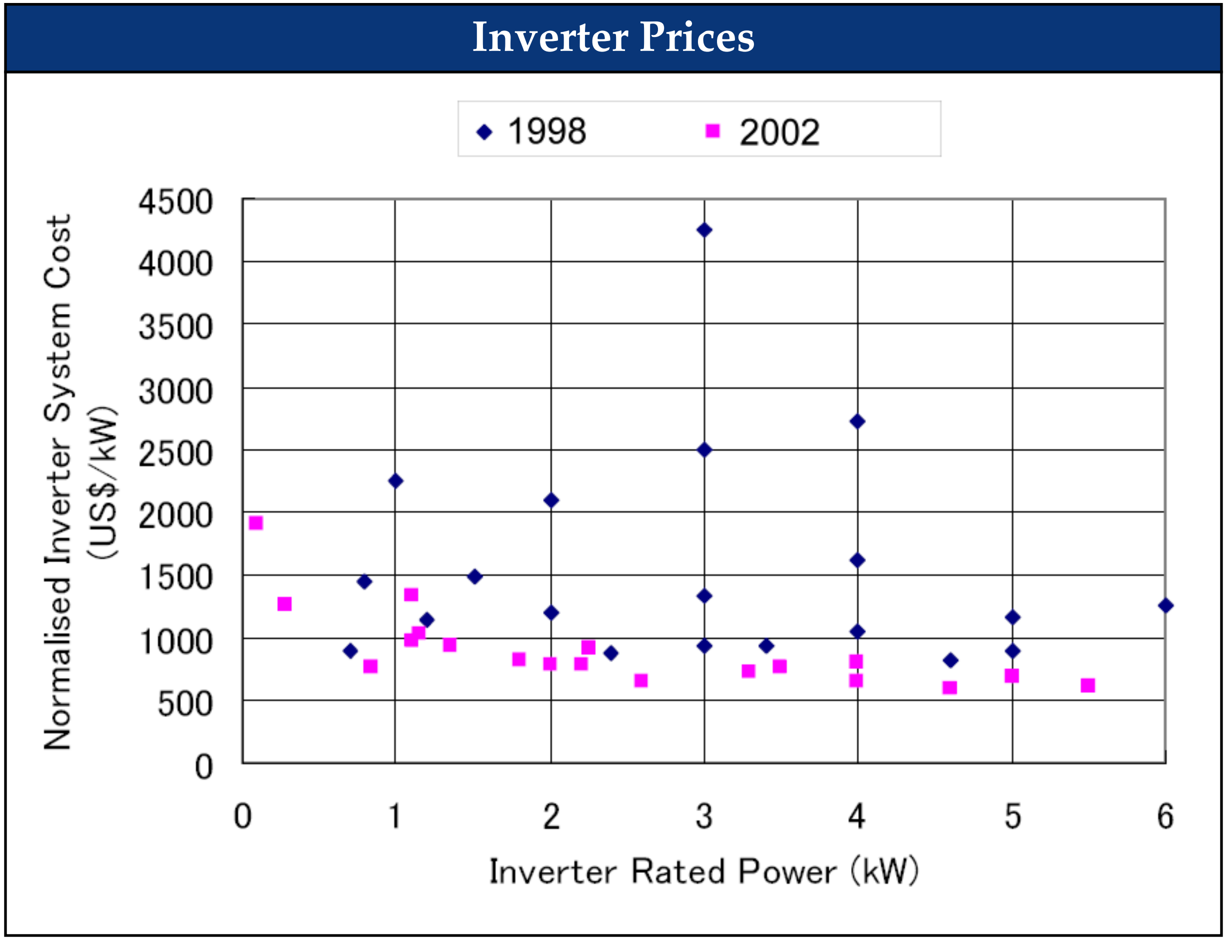
Inverter Prices for TEAM-UP Residential Installations ($/W)



1. From 1996 to 2001, the Solar Electric Power Association (SEPA) managed TEAM-UP, a cost-sharing program funded by DOE to promote grid-tied PV installations.
2. Inverter prices reported for 1997 by SEPA for the TEAM-UP initiative were later determined not to be reported accurately. The data was also not available for the entire sample size. Because of limitations in sizes of available inverters, many were oversized and cost reported on $/kW basis may not accurately reflect the true selling prices being used at the time.

Source: Reference 14

The IEA PVPS program conducted surveys of PV inverters in 1998 and 2002 for U.S., European, and Japanese manufacturers.



- From 1998 to 2002:
  - The general price level of inverters fell by about 40%.
  - Outliers with excessively high prices were completely eliminated from the market.

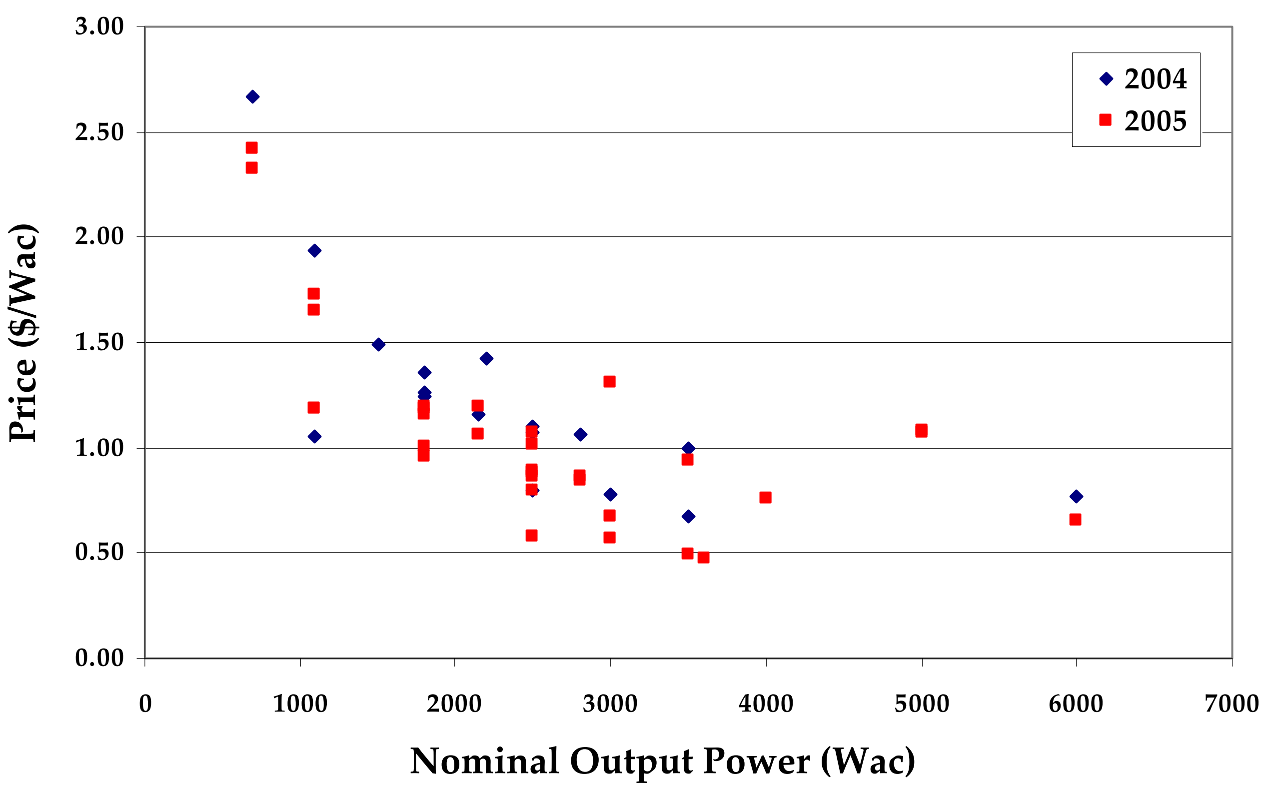
Source: Reference 11

Note:
Each point on the chart represents a particular model's average retail price at the time of the survey.

In 2004, prices for small inverters (<10 kW) in the U.S. ranged from $0.67/W to $2.67/W. In 2005, they ranged from $0.48/W to $2.42/W.

➡ **Our data indicates that U.S. prices have dropped by roughly 10% in the last year.**

U.S. Sample Prices - Residential Inverters ($/W)



Note:
Each point on the chart represents a particular model's average online retail price at the time of the survey.

Source: Navigant Consulting, Inc., 2005.

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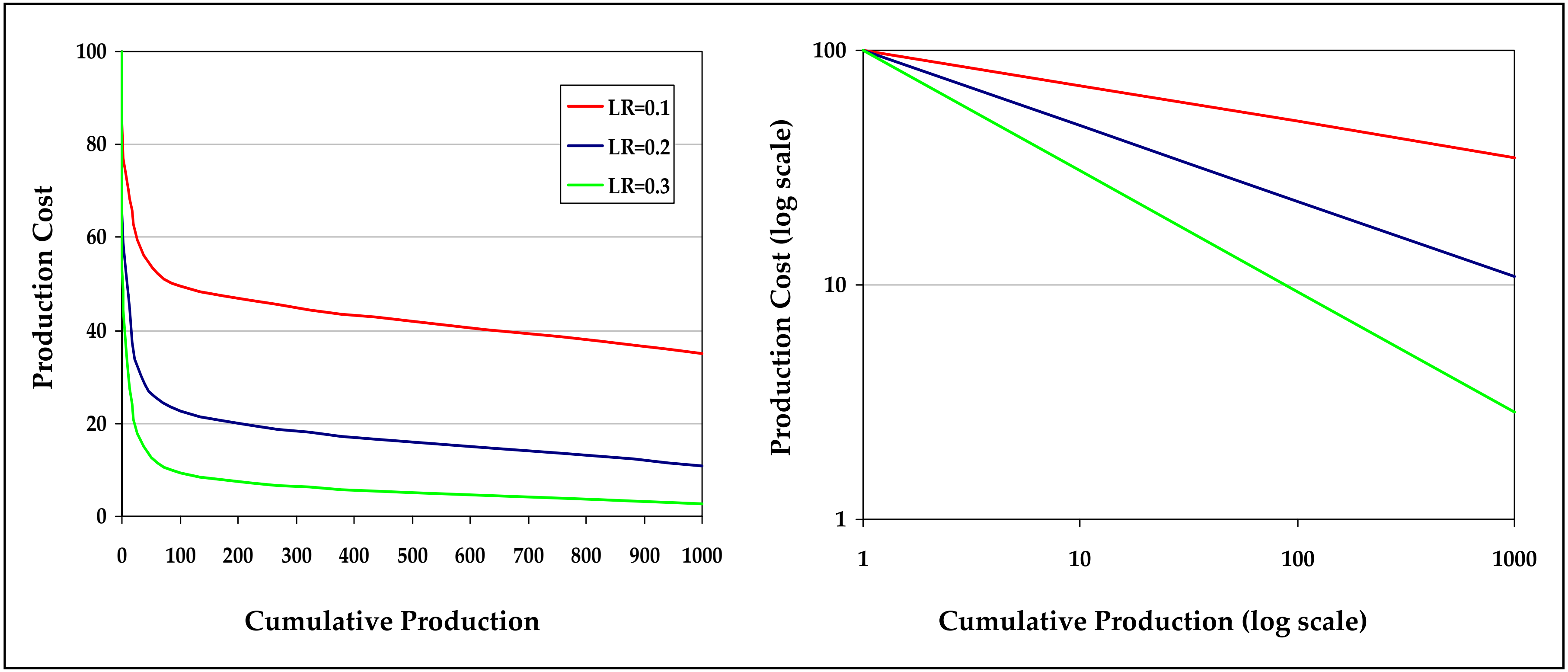
Experience curves model the relationship between cost of production and production volume, which indicates the level of experience.

__Basic Assumption:__ Cost of production declines by a constant percentage with each doubling of the total number of units produced. This cost reduction rate is called the **learning rate (LR)** and ranges from 0% to 35% across various technologies.



The learning rate for PV modules and balance-of-system is about 20%. For inverters, however, the learning rate appears significantly lower.

A comprehensive EU-supported study of prices and production volumes for PV modules and BOS found that the learning rate in the PV industry is around 20%.

➲ For **inverters**, the learning rate is significantly lower**: approximately 10%.**[1]

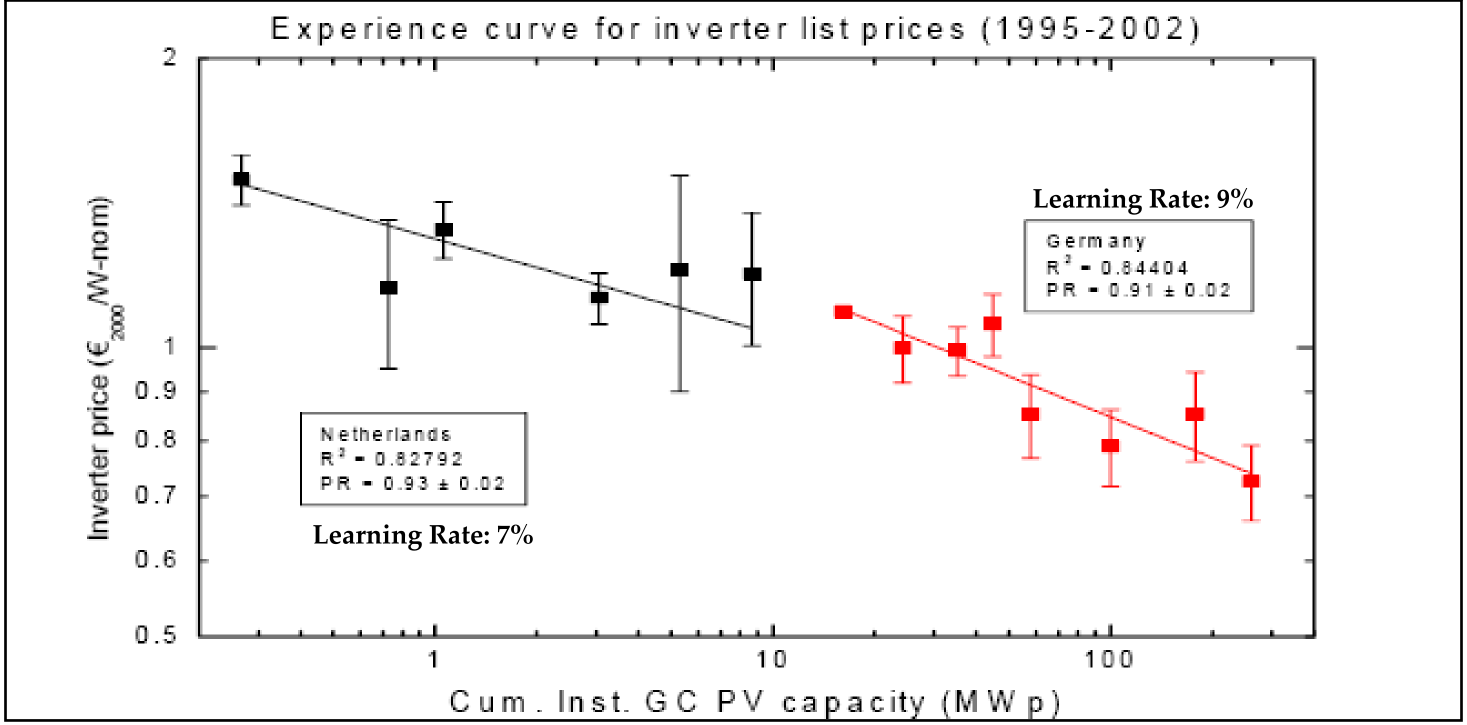
- This figure does not give a complete picture of inverter improvements for two reasons:
  1. This learning rate estimate is based on inverter prices, or up-front costs (on a $/kW basis), rather than lifecycle cost. Therefore, improvements in efficiency and reliability, which improve inverter lifecycle costs, are not taken into account.
  2. Other inverter improvements (e.g. reductions in weight and size, LCD displays, plug-and-play, multi-string, etc.) are also not taken into account.
- In addition, it must be noted that this result is based on an analysis of prices over the 1995-2002 period because of insufficient data prior to 1995. As a result, the learning rate obtained is subject to significant uncertainty because trends in inverter prices may not reflect trends in production costs accurately over periods of less than 10 years.

Source: References 12 and 13

1. The Study points out that this implies a learning rate in excess of 20% for non-inverter balance-of-system. The learning rate for non-inverter BOS is estimated to be 24%.

Data used to estimate the learning ratio for inverters was taken from inverter retail prices in the Netherlands and in Germany (1995-2002).

Experience curve for inverter list prices (1995 – 2002)



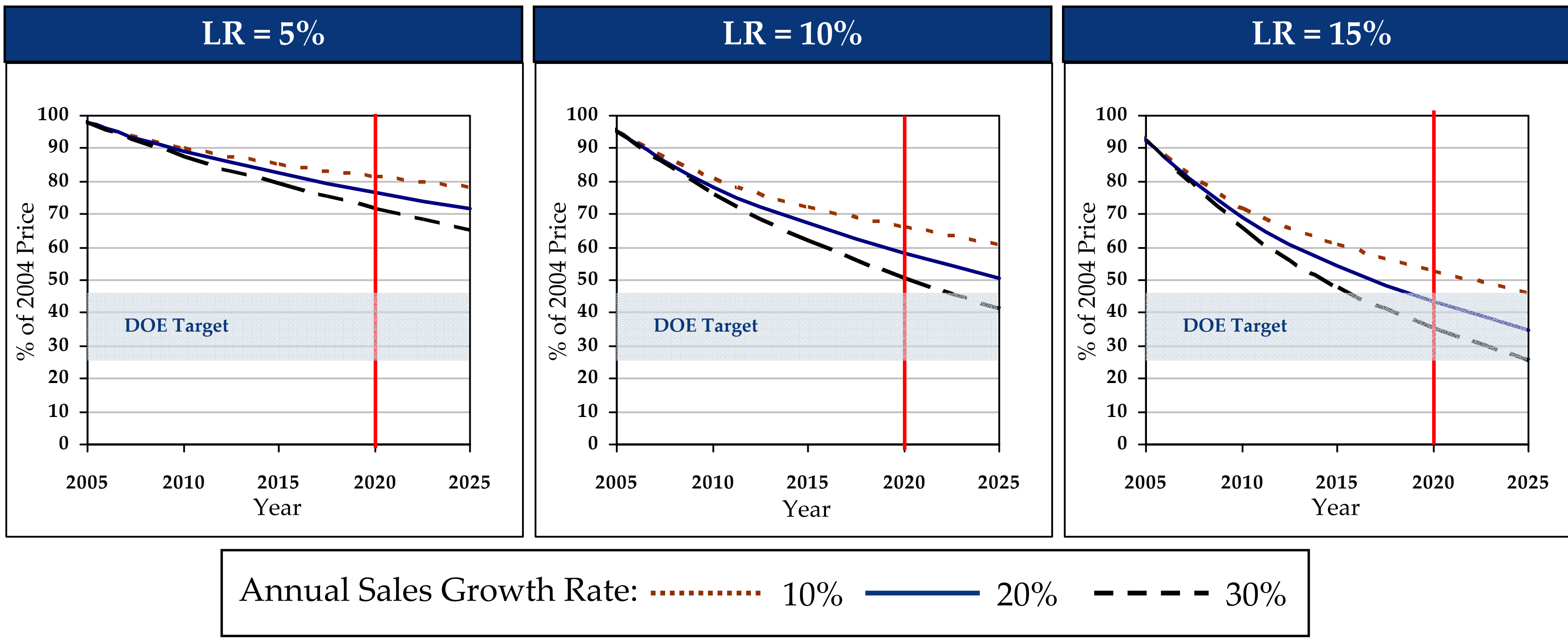
Note: The Progress Ratio (PR) is related to the Learning Ratio (LR): PR = 1-LR

Source: References 12 and 13

Using a 20% growth rate in annual sales and a learning rate of 10%, inverter prices would drop by about 35% in 10 years and 50% in 20 years.

U.S. PV Inverter Prices – Learning Curve Projections

Projections for Various Learning Rates and Industry Growth Rates (2005-2025)



Assumptions:

Installed capacity as of the end of 2004: 163 MW; Sales in 2005: 64 MW.

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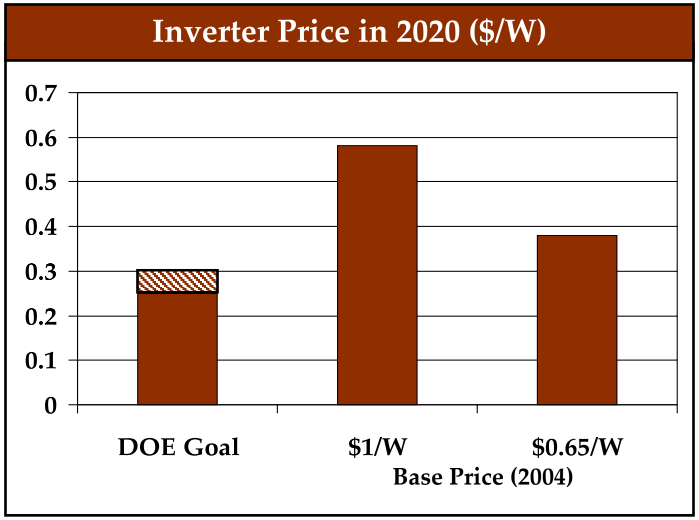
Our central estimate based on learning curve projections shows inverter prices going down by about 42% by 2020.

- This assumes a 20% per annum market growth and a 10% learning curve.
- The DOE target for inverter prices is $0.25-0.30/W by 2020.
  - If the basis for current inverter prices is taken as ~$1.00/W, which is representative of inverters in the 1-3 kW size range, then the price forecast for 2020 is $0.58/W, or about twice the DOE target.
  - If the basis for current inverter prices is taken as ~$0.65/W, which is representative of inverters in the 3-6 kW size range (Xantrex GT 3.0, SMA SB 6000), then the price forecast for 2020 is $0.38/W, still about 30% higher than the DOE goal.



Notes:

- Additional features and other technology improvements have been added over time, such as data logging capabilities, communications and controls and others. Additional features are likely to be added in the future. Therefore, it is difficult to compare inverter prices over time, as the products are not uniform.
- While the DOE goal may appear difficult to achieve on the basis of typical learning curve improvements, it is likely that future products will provide additional customer benefits.

Inverter manufacturers have diverging cost expectations, and projections made in the past have sometimes been overly aggressive.

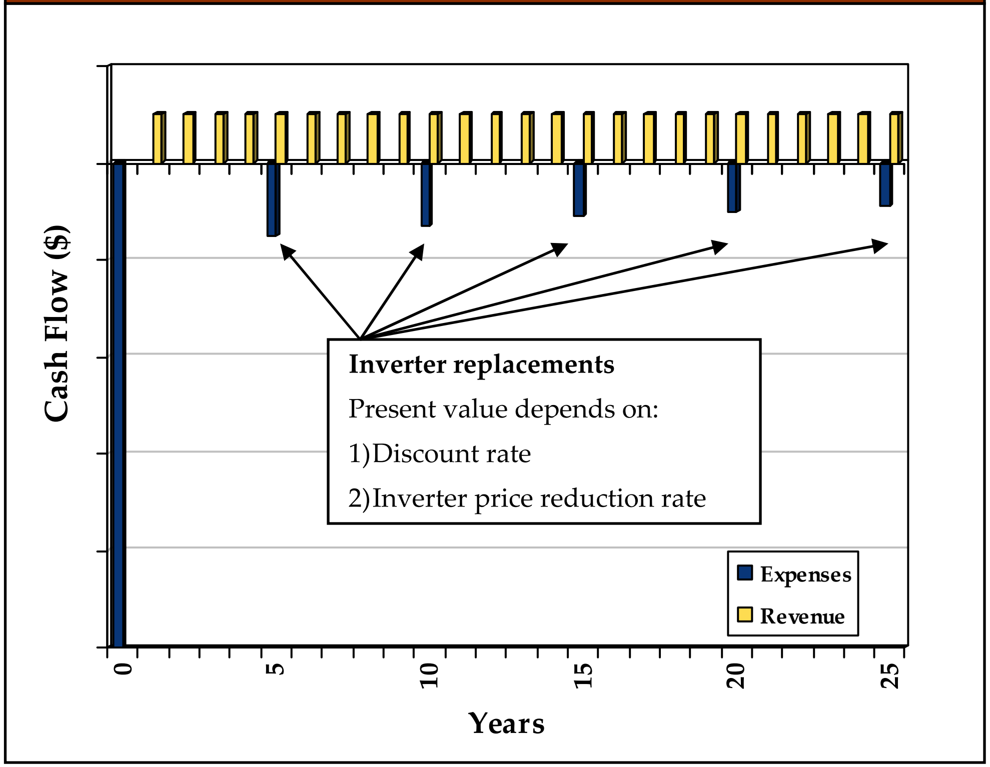
- **SMA** stated in mid-2004 that it wanted to reduce inverter prices by 50% by the end of 2006.[1] The observed evolution in inverter prices since then suggests that it is highly unlikely that this objective will be obtained. However, it is interesting to note that SMA further stated that:
  - ⇨ Cost reductions to less than €250/kW did not seem possible with current technologies. Break-through technologies that may enable further cost reductions beyond 2010 were module-integrated inverters, high frequency converters and high voltage converters.
- More recently, SMA has stated that their goal for inverter costs was to bring down the specific price ($/kW) by 50% every five years.[2]
- **Photon International** reports that inverters prices have gone down by 7% from 2004 to 2005 and that most manufacturers expect costs to decrease by 15%-25% over the next 5 years[3]. However, expectations vary across manufacturers:
  - ⇨ **Exendis** expects reductions of more than 30% over the next 5 years.
  - ⇨ **Sun Power** foresees only slight reductions in cost in the near future and expects inverter prices to stabilize, at least for the next few years.

1. References 12 and 13
2. Reference 16
3. Reference 2

Inverter reliability has an impact on lifecycle cost. Efforts targeting inverter cost reductions should consider reliability improvements.

- The inverter accounts for 10-20% of the initial system cost.
- Inverters generally need to be replaced every 5-10 years, whereas modules and other system components have a life of 25 years or more.
  - » Investment in a new inverter is required 3-5 times over the life of a PV system.

PV Project Simplified Cash Flow



Assumes expenses on other parts of the PV system are small.

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NCI Analysis indicates that the benefits of designing inverters that can operate for 10-15 years or more before replacement are limited.

NPV of lifecycle cost / Initial system cost

Discount rate = 5%; Price reduction rate = 5%

Inverter cost (% initial system)	Inverter replacement interval			
	5	10	15	25+
10%	114.1%	105.0%	102.2%	100%
15%	121.2% →	107.5% →	103.3%	100%
20%	128.3%	110.1%	104.5%	100%

Discount rate = 10%; Price reduction rate = 10%

Inverter cost (% initial system)	Inverter replacement interval			
	5	10	15	25+
10%	105.8%	101.5%	100.5%	100%
15%	108.6% →	102.3% →	100.7%	[illegible]0%
20%	111.5%	103.1%	101.0%	10[illegible]%

<u>**Assuming an initial PV system cost of $8/W:**</u>

NPV of lifecycle cost ($/W)		
9.70 →	8.60 →	8.26

NPV of lifecycle cost ($/W)		
8.69 →	8.18 →	8.06

The benefits of increased reliability must be weighted against the added cost.

Manufacturers generally feel that designing inverters for longer than 15 years is not practical and in general is not necessary. Most manufactures say that the more important issue for consumers is lower first cost.

- **Xantrex, Managing Director**: "Why make inverters with a longer life when the customer is better off replacing the inverter every 10 years or so anyway? The inverters available in ten years will be better products with higher efficiency."
- **SMA America, President**: "Why focus on higher reliability? Our customers worry only about first-cost. In any case, it's more cost effective to just replace the inverter in 10 years."
- **Sustainable Energy Technologies, Director of Operations**: "A 20 year lifetime for PV inverters is <u>at least</u> 10 years away."
- **Mitsubishi**: "A 20+ year life for inverters is impossible. Some parts of the inverters would need to be replaced over such an extended period."
- **SMA, Head of Solar:** "A 20 yr lifetime is not possible."
- **Fronius, Head of Sales (Germany):** "Inverter MTBF may reach 12 years by 2015. A 20 year lifetime can't be achieved."
- **GE Energy** indicated that 20 year life would not be practical without a significant impact on cost. A 15 year life is more reasonable, and that should be reviewed based on life cycle costs impact.
- Contrary to statements made in a recent Photon International article (April 2005), manufacturers and other industry experts we spoke to do not believe that capacitor improvements alone will result in inverters that can "keep going for more than 20 years".

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Many of challenges for PV inverters are a result of low volume manufacturing and an inconsistent regulatory environment.

Manufacturing	1. Inadequate product improvement processes 2. Lack of training 3. Products rushed to market too quickly 4. Lack of good quality control processes 5. Lack of investment in sophisticated testing and manufacturing equipment 6. Components purchased in small quantities
Design/Technology	7. Advanced semiconductor devices for switching needed (e.g. SiC devices) 8. Need to improve efficiency 9. Limited experimentation with alternative inverter topologies 10. Capacitors available on the market are not well suited to PV inverter applications 11. Lack of sophistication in inverter designs (e.g. leveraging synergistic applications)
Regulatory	12. Regulations differ across PV markets 13. Regulatory complexity generally increases cost 14. US grid-interconnection regulations are a heavy burden on inverter manufacturers 15. US requirements for PV installation increase costs substantially 16. Utility resistance to ungrounded systems
Policy	17. Few states have adequate incentives to promote PV market growth 18. Changing policies hamper long term investment decisions

Note: The numbers in the above list do not indicate priority ranking.

Manufacturers generally assert that production volume is the most powerful factor in driving down inverter cost, but design improvements also play a role.

"Economies of scale will create a downward pressure on PV inverter costs."

Sun Power, North American Manager, June 2005

"Sales volume in each market will drive the price of inverters."

Siemens, June 2005

"Our costs have gone down 50% due to volume. Volume is the only cost driver."

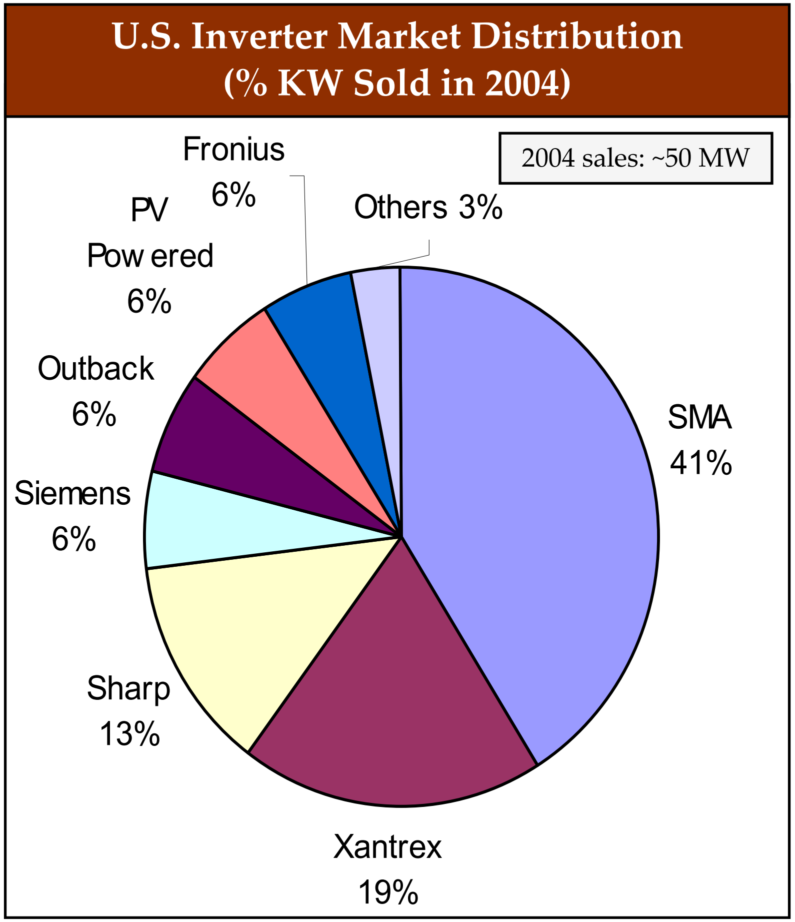
SolarMax, Managing Director, June 2005

"SMA believes that cost reductions will be a combination of new designs, new topologies, less components, and higher quantities."

SMA, Head of Solar Division, June 2005

- There does not a appear to be a "silver bullet" technology on the horizon that could cause a major drop in inverter cost.
- The industry anticipates incremental cost and performance improvements for the foreseeable future.

The U.S. PV inverter supplier base is dominated by 3 companies with 75% of the market, while many smaller players share the remaining 25%.



Source: Navigant Consulting Analysis, August 2005

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Help manufacturers improve the quality of their product through better testing and failure documentation.

Manufacturing and Testing
▪ **Inverter testing** at Sandia National Labs is extremely valuable to the industry and continued support of development of testing protocols is important to the industry.
▪ **Documentation and analysis of failure** in the industry is not conducted uniformly. A possible role for government would be in collecting and documenting inverter failures to share with the industry.
▪ **Comprehensive information on inverter components** (capacitors, electrical connectors, power semiconductors, etc.) would assist manufactures in identifying the best products.
▪ Manufactures would benefit from understanding the costs and benefits of **HALT and HASS testing** programs. Government could assist by providing general guidelines and experience from other industries.

Promote innovation in inverter technology and design through experimentation, modeling, and public-private partnerships.

Technology and Design
▪ **Modeling tools** would be helpful to manufactures, but developing accurate models is challenging. An assessment of issues and needs related to modeling would be appropriate before embarking on new modeling efforts.
▪ A role for government may be in support of testing and evaluating **experimental topologies** as a means of advancing the industry.
▪ Follow-on **public-private R&D partnerships**. One such partnership, the HRII program, is generally considered to have been successful.

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Encourage improvements to regulations and help manufacturers achieve compliance, and support industry growth.

Regulatory

- **Studies on the pros and cons of transformerless inverters** as a means of educating inspectors and regulators would be beneficial.
  - Magnetek announced on January 9th, 2006, that its transformerless Aurora inverters have been listed by CEC. (source: Business Wire)
- **Standards** for grid connection, communications, and performance metrics are a major complaint of manufacturers, but possible roles for DOE in this area may be limited.

Policy

- **Analysis of the various Federal, State, and municipal support programs** available to PV. A better understanding of the impact of incentives and the interaction between them can help to guide policy, and will be increasingly important to future industry growth.

Larger manufacturers generally do not see government support as critical, but they can nevertheless benefit from it.

- In general, larger companies in the PV inverter business view the role of government in providing assistance (via programs to reduce cost and increase reliability) as being less critical to their success and the long term future of the industry.
  - Most larger companies NCI spoke to believe that increasing sales volume is the single largest factor that will lead to lower cost and higher reliability for PV inverters.
- Despite these views, introducing a new inverter product has proven to be a risky venture for some of the larger companies. For example:
  - Xantrex experienced significant problems with their early PV inverters and ended up losing market share to new European market entrants.
  - Philips entered the PV inverter market in Europe, only to exit a few years later after experiencing significant technical problems with their first product.
- Even large manufacturers can benefit from government support for inverter development.
  - GE has commented that their involvement in HRII has significantly impacted product development, by allowing them to explore options that would otherwise have been left aside.

Support for smaller inverter manufacturers can benefit the PV industry as a whole.

- The PV market will be in a critical growth phase over the next 5-10 years, continuing to require significant policy and market support to achieve the overall cost and performance required for a sustainable market.
- If small manufacturers have more difficulty meeting the reliability requirements of the market and cannot afford to provide adequate after-sales service, it could hurt the PV industry as a whole (poor inverter performance will hurt the image of PV installations in general).
- While some consolidation in the inverter business should be expected, the benefits of competition and innovation provided by the smaller companies are likely to be important to the industry at its current, early stage of development.
- Given their small size and relatively low level of sophistication, many PV inverter manufacturers may benefit tremendously from small improvements to design and manufacturing (e.g. low hanging fruit for cost and performance improvements).

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Achieving the targeted improvements of lower cost and higher reliability for inverters is not a foregone conclusion for the industry.

- Based on learning curve forecasts, the targeted cost reductions for 2020 will not be achieved with current market growth and learning rate levels.
  - Significant uncertainty exists around the potential for future market growth to exceed current levels for an extended period of time.
  - Additional cost reductions will require an acceleration of learning effects.
- Reliability and life issues for inverters have the potential to damage the reputation of the industry and long term adoption of PV.
  - Because of market demands, manufacturers today are focused on lowering first cost over improving reliability.
- With no "silver bullet" technological breakthroughs on the horizon, the evolution of inverters will be driven by incremental design and manufacturing improvements.

NCI's assessment is that there is an important role for government to support PV inverter improvements for the next several years.

Government efforts should focus on working with manufacturers to promote and facilitate product development and process improvements.

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Many potential roles for government were identified that can help to improve the chances that DOE program targets are achieved.

What are the critical cost and performance improvement needs for PV inverters that government should support to promote PV market growth?

Do PV inverters face challenges in meeting the U.S. DOE's Solar Energy Program Technologies targets?

- Sales volume increases and learning curve improvements alone appear unlikely to achieve the targeted inverter selling price of $0.25-0.30/W by 2020.
- Inverter lifetimes greater than 15 years appear difficult to achieve.
- Improvements in manufacturing, design and technology are needed to achieve the price and performance targets.
- Reducing regulatory complexity and long term, consistent policy will also be required.

Is there a clear understanding and consensus for addressing key PV inverter challenges?

- Manufacturers and industry experts do not agree on needs to address key inverter challenges.
- Support is needed in several areas:
  - *Manufacturing and testing improvements*: process improvement, training, quality management, HALT/HASS assistance, and documenting field performance data.
  - *Design*: alternative topologies, thermal management, modeling, and DER inverters.
  - *Technology:* advanced switching, capacitors, and components.

What role should government play in addressing the key challenges that PV inverters face?

- Assistance with testing methodologies for inverter ratings. Access to training in manufacturing processes, and quality control. Support to understand field performance, and failure data.
- Support for public-private partnerships for R&D on new technologies, topologies, and modeling.
- *Information and analysis to support:*
  - Evaluation of regulatory and safety requirements.
  - Evaluation of alternative policy approaches.

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7. Sustainable Energy Technologies
8. Heliotronics
9. SunPower
10. Siemens
11. PowerLight
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Many manufacturers are small startups that lack the internal processes needed for quality control of product development and manufacturing.

1. Inadequate product improvement processes	➲ Internal processes that provide the discipline, resources, and commitment needed for continuous product improvement are lacking among many small inverter manufacturers.
2. Lack of training	➲ Inverter manufacturers typically have a small workforce, where employees are asked to perform several different tasks, often without adequate training.
3. Products rushed to market	➲ The pressure to ship as soon as possible leads manufacturers to produce poorly written and insufficient documentation, leading to low installer/customer satisfaction, and expensive customer support.
4. Lack of good quality control processes	▪ Due to limited resources, inverter manufacturers compromise quality control: – Inspections that can identify problems early in the manufacturing process are not carried out properly. – Proven methods such as "Highly Accelerated Life Tests" (HALT) are often overlooked or not used. – Failure documentation is inadequate or non-existent. Inverter manufacturers typically have little information on failures of their units in the field or during testing, making it difficult to identify problem trends and take corrective action. ➲ Inadequate quality control leads to reliability problems and ultimately imposes additional costs on inverter manufacturers.

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Low production volumes make it impossible for manufacturers to take advantage of mass production technologies and volume discounts.

5. Lack of investment in sophisticated testing and manufacturing equipment	▪ Most inverter manufacturers are small companies – They cannot afford expensive testing equipment based on their modest sales volume. – Low production volumes cannot justify the investment needed for an automated production line, and they do not have the needed expertise. ➲ Inverter manufacturers cannot make investments that would greatly improve product quality because their sales volumes don't currently justify it. Proven methods to detect design flaws such as 'Highly Accelerated Life Tests' (HALT) are not used.
6. Components purchased in small quantities	▪ Most inverter manufacturers purchase components in small quantities due to modest sales volume: – They cannot benefit from discounts offered on large orders and better supply chain management – With each new order for a given component, inverter manufacturers often purchase from different suppliers, depending on where they can find the best price. This results in wide component variations and problems with the final product. – Inverter manufacturers typically do not audit their suppliers for quality control. ➲ Purchasing components in small quantities leads to higher cost, lower quality and impacts reliability.

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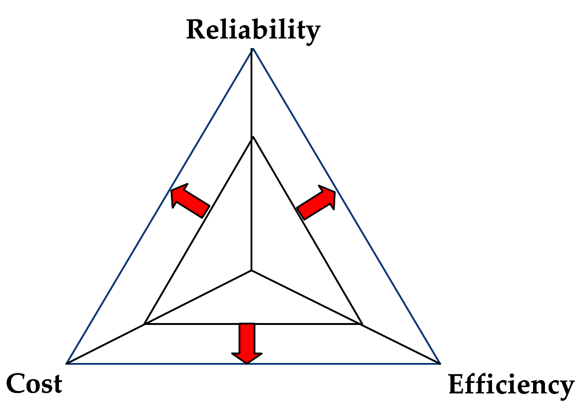
Components available on the market today do not adequately meet the technical requirements of the inverters.

7. Advanced semiconductor devices needed for switching. (e.g. SiC devices)	▪ The various switching devices used in inverters to convert DC to AC current are another weak point for inverter reliability. ▪ There are technologies (e.g. SiC switches and integrated circuits) that show promise for better performance, but inverter manufacturers have little weight in influencing the direction of R&D and most have limited internal R&D capabilities in this area. ➲ Switch reliability is currently inadequate for PV inverters, and is a source of heat generation. New developments, such as SiC are a power electronics/semiconductor industry issue and inverter manufacturers will have little influence in directing research in this industry.

Lack of resources and design experience hampers inverter product design and development improvements.

8. Need to improve efficiency and the standards for ratings[1]	▪ Maximum efficiencies are typically near 95% for U.S. inverters, but manufacturers do not have consistent methods for rating inverters and can chose any point over the load curve for quoting the rating. ▪ Consumers do not have an easy way to compare inverters based on efficiency. ➲ Certification processes could provide standard test methods for rating efficiency. Design improvements and elimination of transformers could improve efficiencies by 2% or more.
9. Limited experimentation with inverter topologies	▪ Converting DC to AC current can be done using a great variety of approaches. The various designs that inverter manufacturers incorporate in their inverters to accomplish this task are known as "topologies". ▪ Various topologies yield different inverter performances in terms of reliability, efficiency, and cost. While there is generally a trade-off between these 3 objectives, some topologies are simply better than others and can improve inverters in every respect.  ➲ Inverter manufacturers do not have the resources to experiment with topologies extensively, so potential inverter improvements may be lost.

1. The CEC recently adopted and is using a major portion of Sandia's Test Protocol for Certification of Inverters. Several states are now accepting California's published numbers. Still more needs to be done for features such as MPPT.

Component limitations and lack of design experience hampers inverter product design and development.

10. Capacitors available on the market not suited for PV inverter applications.	▪ Capacitors are often cited as the most severe reliability problem for inverters. They are extremely sensitive to temperature (electrolytic capacitors), and one manufacturer reports that an increase of even 10°C can halve capacitor lifetime (Heliotronics, President, January 2005). ▪ There are capacitor technologies that show promise for better performance in PV inverters, but R&D in the capacitor industry is limited ▪ The capacitor industry is not responsive to PV inverter needs because PV inverters account for a small fraction of capacitors sold. ➲ Capacitor reliability is currently inadequate for PV inverters, and there is little that inverter manufacturers can do to influence the capacitor industry, other than design around the problem, which impacts cost.
11. Lack of sophistication in inverter designs	▪ Engineers from other, more mature industries where power electronics are used have commented that inverter designs are unsophisticated and could often be improved with some fairly easy fixes (Sun Power, North American Manager, June 2005). ➲ Many PV inverter manufacturers lack knowledge or broader experience in power electronics design.

Lack of an international standard creates regional markets for inverters. In the U.S., regulations are particularly burdensome for manufacturers.

12. Regulations differ across PV markets	▪ Regulations for grid-connected PV inverters vary across countries. In Europe, requirements across some countries (e.g. Germany, the Netherlands, Switzerland) vary only slightly and manufacturers are able to use the same inverter models to reach these markets. ▪ Requirements are most stringent in the U.S.. International manufacturers who wish to serve this market need to design models specifically for the U.S. in order to meet regulations. ➲ This lack of uniformity creates regional markets, making it extremely difficult for manufacturers to create a global product (as with modules). By preventing standardization across markets, potential economies of scale are lost.
13. Regulatory complexity increases cost	▪ Regulatory differences between states or countries require product modifications and specialization which increases costs for manufactures. ▪ Different safety requirements, interconnection or testing requirements increase the cost for manufacturers for selling their products in different markets. ➲ Product lines vary by market and some companies chose to focus on specific states and not others. These issues lead to higher prices in all markets.

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Requirements for grid connection vary significantly in spite of UL and IEEE standards that are expensive for manufactures to meet.

14. U.S. grid-connection regulations are a heavy burden on inverter manufacturers	▪ U.S. manufacturers face confusing regulations. – In 2005, UL 1741 and IEEE 1547 have apparently been consolidated in a way which should help to resolve some of the confusion around compliance with these two standards. Ongoing changes to the requirements of these standards is likely to continue to create challenges for manufactures. – Acquiring the UL 1741 standard costs on the order of $100K, a substantial amount for small players and modifications typically requires additional testing, which is a barrier to making improvements. – Utilities can also adopt their own standards, adding to the complexity. ➲ UL standards are a damper on innovation because product improvements require new testing for modest changes to designs. Utilities and local government can also require their own standards which increases cost.

Inverter and installation costs are significantly higher in the U.S., driven by complex requirements and local codes that still requiring grounding.

15. U.S. requirements for PV installations increase costs substantially	▪ Manufacturers who sell PV inverters in European markets and in the U.S. report that installation costs are substantially higher in the U.S. – The installed cost of a 5 kW system is on the order of €4.2 – 5.0/W in Germany, as opposed to \$6.50 – 9.00/W in the U.S. (Head of Solar Electronics Division, Fronius, January 2005) – The cost of installation of a 5 kW system is on the order of €700/kW (\$833/kW) in Germany, as opposed to \$1,400/kW in the U.S. ▪ One of the areas of higher cost in the U.S. is related to the requirements for externally accessible AC disconnects and conduits for DC cabling. ➲ Roughly speaking, installation costs for PV in the U.S. are nearly twice that of Germany
16. Utility and local resistance to ungrounded systems	▪ Ungrounded PV array installations are allowed by the 2005 National Electric Code, which means that transformerless inverters could now be used in the U.S. ▪ However, it is expected that these systems may be difficult for U.S. inspectors and regulators to accept without substantial additional work on local codes and standards. ➲ Resistance to transformerless designs impacts opportunities for significant inverter improvements: higher efficiency, lower weight, and lower cost.

PV market growth is restricted to a handful of states, limiting prospects for inverter manufacturers and hampering investment.

17. Few states have adequate incentives to promote PV market growth	▪ Several states have very good incentives for PV (e.g. CA, NY, NJ), but many states in areas such the Southeast have no buy-down programs or other incentives to stimulate installations of PV. ➲ Where incentives are inadequate, the PV market will see very limited growth, and potential economies of scale in the US for inverter manufacturers will remain untapped.
18. Changing policies hamper investment	▪ Major investment on the part of inverter manufacturers depends on a high level of confidence in future income streams. ▪ Uncertain or changing incentives for PV create the wrong kind of incentives for manufacturers, who respond by putting their product on the market as quickly as possible, without investing in lengthy product development or sophisticated assembly and testing equipment. ➲ Without stable PV support policies, inverter manufacturers will be unable to make substantial investments to improve their product.

B Roles for Government

Inverter testing at Sandia National Laboratory helps manufacturers experiment with innovative designs and improve their product.

Inverter Testing

- **Benchmarking tests** to evaluate inverters against manufacturer specifications. Manufacturers generally agree that a comprehensive program of inverter testing and performance reporting would be very valuable to the industry.
- **Development testing** protocols to assist manufacturers in testing new inverter models.
- **Utility compatibility and islanding tests**. This type of testing provides manufacturers with information on their inverters' ability to meet UL 1741 requirements. Various utilities also request system specific tests to be performed in order to understand the effect of PV inverters on their grid. Debate exists regarding the value of this, but it will remain a requirement.
- **Temperature evaluations**. These tests allow manufacturers to study temperature issues and test various strategies for thermal management, which are critical for product reliability.

Verification, validation, and characterization is extremely valuable to inverter manufacturers, who often do not have extensive in-house testing capabilities. Sandia should be provided with the resources necessary to support development of inverters for the U.S. market.

Government can assist manufacturers in improving product reliability by studying and documenting failure of inverters in the field.

Documentation of Inverter Failures

- Data of failure of inverters in the field is lacking. Most inverter manufacturers generally know the number of shipped units that were returned by customers, and little more. They generally do not look into what caused the inverter to fail.
- Larger companies are apparently capturing and documenting information on inverter field problems, but information is considered confidential.
- A comprehensive database of inverter failures would enable manufacturers to understand areas of weakness in designs and take corrective measures.

A possible role for Government would be to conduct an extensive study of PV installations to document inverter failures and provide the results to manufacturers.

Documentation of information on key inverter components would assist manufacturers with design choices.

Component documentation

- Inverter manufacturers have commented there are substantial differences in the performance of components (e.g. capacitors) available from different suppliers.
- Inconsistent specification, data sheets and testing results exist on some of the key components for inverters (e.g. capacitors, fans, electrical connectors, power semiconductors, etc…) making it difficult for manufactures to make proper comparisons of options.

A comprehensive study of inverter components would help manufacturers identify the best available products.

However, because components used in inverters are also used in many other applications, it is likely this type of work should be conducted as cross-cutting research to support DG inverters and power electronics.

Manufacturers need modeling tools to help with product development, but do not have the resources to develop them.

Modeling Tools

- Manufacturers lack the resources to develop modeling tools for inverters. Such tools would enhance manufacturers' ability to explore options and select the optimal design.
- Sandia has the expertise to develop inverter models and this type of work has been done in the past. However, one Sandia expert has commented that modeling of inverters was very difficult. But while completely accurate models may be nearly impossible to achieve, simplified models could still be useful.

While modeling tools would help manufacturers develop their products, developing such models is challenging. Therefore, resource requirements and the limitations in achievable results with this type of work needs to be examined before extensive investment in new modeling tools.

Manufactures would benefit from understanding the costs and benefits associated with HALT and HASS testing.

HALT and HASS Testing Methods

- **Highly Accelerated Life Testing (HALT).** This type of test subjects the inverter to extreme operating conditions in order to identify weak points in reliability for new designs. Some of the larger manufactures conduct this testing, but most do not have resources or an understanding of proper testing procedures to follow.
- **Highly Accelerated Stress Screening (HASS).** Production testing to screen products knowing the operating and destruct limits based on HALT testing. Few manufactures understand how to perform this testing and its value for PV inverters is not understood by most.

Information and guidance regarding the value and applicability of HALT and HASS testing for inverters would benefit the industry. The tradeoffs on cost and reliability and life improvement need to be more fully understood.

A possible role for government would be to provide assistance to manufacturers in setting up HALT and HASS programs as well as general guidelines to follow.

The success of HRII indicates that government should consider funding another similar initiative.

Public-Private R&D Partnership

- The High Reliability Inverter Initiative (HRII) launched in 2002 will come to an end this year. The contractors selected (GE, Satcon, Xantrex) are developing prototypes of advanced inverters. At least one manufacturer has commented that their involvement in HRII has significantly impacted product development, by allowing them to explore options that would otherwise have been left aside.
- It should be noted that Sandia received many responses to their RFQ, 6 of which were deemed excellent. But only 3 manufacturers could be selected due to funding limitations (~$5M).
- Programs such as this may be appropriate for development of advanced components such as switches, capacitors and connectors that would benefit the broader DER inverter industry.

A formal review of the HRII program should be completed and shared with the industry to allow others to understand some of the key findings.

At this point, the results of HRII appear promising. Pending an evaluation of final results and appraisal of HRII success, another similar initiative may be a good use of DOE funds.

Use of similar approaches for DER inverter components should be explored.

Innovative inverter topologies could be a source for additional cost, reliability and performance improvement and a potential role for government may be to fund studies to understand potential benefits.

Alternative Inverter Topologies

- Innovative control and inverter design topologies have the potential to be a source of cost reduction, improved thermal management, and improved reliability. Several manufactures have noted that there could be many advantages to the exploration of alternative topologies.
- Alternative topologies could be used to standardize "sub components", that could be used across product lines or in power electronics for other DER products.

Government could consider funding studies on the potential benefits of alternative inverter topologies. Many benefits have been suggested, but there does not appear to be significant direct evidence of the specific gains that might be achieved.

Research could focus on experimental topologies, with the objective of advancing the industry.

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Government should consider conducting an assessment of performance, cost and reliability benefits that could be derived from wider adoption of tranformerless inverters.

Benefits and Issues Associated with Ungrounded Arrays

- The 2005 National Electric Code allows the use of ungrounded arrays, but local electric code and utility interconnection in the US still requires grounding. There are efficiency and cost benefits associated with eliminating transformers, but there is not acceptance of other protection schemes and there are concerns about safety at local and utility levels. Local inspectors and regulators do not generally accept other protection schemes.

A sponsored study on the pros and cons of ungrounded arrays and elimination of transformers could be a general benefit to the DER industry. There is significant experience in Germany with tranformerless inverters and transferring this knowledge to the US would be of value to the industry.

Standards are a major complaint of manufacturers, but possible roles for DOE in this area may be limited.

Standards

- **Grid connection**: Manufacturers repeatedly ask for standards to be harmonized, for ungrounded PV arrays and transformerless inverters to be accepted, and for relaxation of installation requirements that retain safety.
- **Communication:** Standards for communicating PV system information are needed for data monitoring and for utility interaction. Without a single, universal standard, manufacturers will develop proprietary standards that will lead to fragmentation and hamper growth of this technology.
- **Performance metrics:** Sandia and Endecon Engineering (now BEW) are currently developing the PV Inverter Performance Test Procedure. Manufacturers have been asking for this type of standard, and support for this activity should continue.

Grid connection and installation: These standards are the domain of organizations like UL (UL 1741), IEEE (IEEE 1547), and NFPA (NEC 2005). However, DOE may be able to influence these organizations or provide leadership to help bring about the changes that inverter manufacturers are asking for. In addition, the following specific recommendations have been made relative to UL 1741:

1. Subsidize the cost of acquiring the UL 1741 standard.
2. Subsidize the cost of attending UL 1741 meetings to encourage industry participation.

Communication: EPRI is leading the effort to develop a communication standard for DER. DOE should support this initiative.

Performance metrics: Sandia and Endecon Engineering are currently developing the PV Inverter Performance Test Protocol. Manufacturers have been asking for this type of standard, and support for this activity should continue.

Understanding the role of incentive programs and policies for PV will be critical to the long term growth necessary to meet cost, performance and reliability goals.

The Impact of Alternative Policies and Incentives for PV

- Increasing market volume is one of major drivers in achieving cost and performance goals for inverters. Market volume in the US is growing, but not to the degree it has in Germany and Japan.
- There is significant fragmentation in policies to promote the adoption of PV. California, New Jersey and New York lead the country with programs to buy down the price of new systems. National policy provides investment tax incentives. European feed-in tariffs have developed a much more rapidly growing market and are driving most of the investment in the industry.
- An assessment of impact of alternative policies would benefit the industry.

Government could fund a study of the impact of PV policy programs with the objective of understanding the relationship of program design to market growth and options for making U.S. policies more effective. Understanding the interaction of Federal, State, and municipal programs will be increasingly important to further industry growth.